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RESEARCH REPORT

Intracerebral source generators characterizing concentrative meditation

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Abstract Previous researchers have studied meditation practices as a means to understand consciousness as well as altered states of consciousness. Various meditation techniques, such as Transcendental Meditation (TM) and Qigong, have been explored with source localization tools; however, the concentrative meditation technique has yet to be fully studied in this manner. The current study demonstrates findings, which outline differential activation in a self-referential default network during meditation in participants who espouse themselves as regular concentrative meditation practitioners, as well as comparisons with a control group practicing a modified version of the relaxation response. The results are compared with other putative experimental findings employing other meditation techniques, and the findings outlined in the current study are discussed with respect to changes in perceptual awareness often reported by meditators.

Keywords Source localization · Concentrative meditation · Quantitative electroencephalography · sLORETA · Default mode network · Temporal processing · Time dilation · Relaxation response

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Introduction

Recent behavioral and neuroscientific studies have highlighted the importance of studying meditation states and traits (Raffone and Srinivasan 2010) from various techniques as they may produce unique neurophysiological profiles (Cahn and Polich 2006). Davidson and Goleman have proposed two poles characterizing meditation techniques, which involve concentrative on one end and mindfulness on the other (1977). These practices have more recently been assessed and termed focused attention and observational monitoring, respectively (Raffone and Srinivasan 2010). Whereas observational monitoring or mindfulness meditation would involve the non-judgmental monitoring of one's thoughts and experiences, in the focused attention (i.e., concentrative) meditation style, attention is focused on a given object and this attention is sustained (Davidson and Goleman 1977; Raffone and Srinivasan 2010). The focus of the present study was on delineating the intracerebral source generators characterizing a concentrative meditation practice in subjects who espoused themselves as regular practitioners of the technique, as well as comparing these profiles against a group of controls during relaxation.

Various meditation techniques have been explored using EEG measures, and it appears that different meditation practices or techniques demonstrate their own unique EEG profiles. While investigating the Qigong meditation technique, Pan et al. have related frontal midline theta activity to the concentrative aspect of Qigong meditation practices when compared to non-concentrative Qigong engagement, regardless of subjects' experience (Pan et al. 1994). In a separate study involving a meditation intervention, when mindfulness meditation was compared with concentrative meditation, the mindfulness condition produced more

posterior and lateral frontal delta, frontal and central theta, central-parietal and right temporal alpha, and central-parietal and left prefrontal beta-1 activity than the concentrative condition; whereas, the concentrative condition produced greater right prefrontal and bilateral occipital beta-2 power than the mindfulness condition (Dunn et al. 1999).

Using source localization methods for discerning intracerebral generators of electrical activity, such as low-resolution electromagnetic tomography (LORETA), have yielded interesting results with respect to EEG profiles for different meditation techniques. Using eLORETA, Travis et al. explored Transcendental Meditation (TM) practice (2009). The results indicated that, compared with baseline, alpha-1 power generation occurred in the anterior (BA33), dorsal (BA24), and posterior cingulate gyri (BA30). Similarly, BA18 and BA19, of the visual association area, were more active in the alpha-1 band during meditation; however, beta-2 characterized eyes-closed rest in the visual association cortices (BA18 and BA19) (Travis et al. 2009). These areas overlap with the default mode network (DMN) (Raichle et al. 2001), and Travis et al. (2009) hypothesize that the greater activation in DMN areas during TM suggests that meditation may improve baseline states of cerebral functioning.

Not only has TM been studied with LORETA programs, but also practitioners of the Qigong technique have been studied with EEG source imaging. A comparison of meditators and controls during a resting condition indicated significantly different baselines. In the Qigong meditation group, subjects displayed stronger delta activity in the prefrontal cortex regions in the left and the right hemisphere than the controls (Tei et al. 2009). Meditators also elicited more left and right hemispheric delta in the anterior cingulate (BA32) than the control subjects (Tei et al. 2009). Moreover, the meditator group displayed significantly weaker delta activity in the motor and somatosensory association cortices (BA4, 6, 7), visual association cortex (BA18, 19), the left temporo-parietal junction (BA22, 39, 40), the left precuneus (BA31), and bilateral fusiform gyrus and right parahippocampal gyrus (BA30). Although the aforementioned study only explored baselines, it still provides insight into the baseline resting differences between control subjects and participants espousing themselves as meditators.

Functional neuroimaging studies exploring various meditational techniques also suggest that the different practices are associated with distinct neurophysiological profiles. Concentrative meditational practices that focus on mantra repetition have elicited the activation of fronto-parietal networks associated with internalized attention (Brefczynski-Lewis et al. 2007; Aftanas and Golocheikine 2001, 2002a, b, 2003; Newberg 2001; Ritskes et al. 2003), whereas meditational techniques that focus on the breath may elicit additional activation of paralimbic regions such as the insula and anterior cingulate (Farb et al. 2007; Hoelzel et al. 2007; Lazar et al. 2000). Furthermore, techniques that focus on a highly emotive component elicit frontal-limbic activation (Lou et al. 1999; Lazar et al. 2000). Based on the results from the aforementioned studies, which have been succinctly integrated in Rubia (2009), we have hypothesized that concentrative meditation with focus on breathing will involve paralimbic and cingulate activation during the meditational practice, when compared to baseline.

The literature has outlined EEG source imaging results with Qigong and TM meditation; however, little research utilizing quantitative EEG and source localization (i.e., LORETA) has been conducted with respect to the concentration meditation technique in subjects espousing themselves as regular concentrative meditation practitioners. It is of interest to examine the pattern of activation during concentrative meditation practice and baseline conditions, as reflected in EEG source localization. Typically, meditation studies focus on group differences based on cumulative experience (i.e., Lavallee, Koren, Persinger, accepted; Aftanas and Golocheikine 2001), whereas relatively few studies employ a control group for comparison. The control group from which the concentrative meditators were compared to consisted of university students (similar population) with no prior meditation experience. The primary difference was that during the meditation/sitting period, the control group subjects practiced a modified version of the relaxation response as this technique (Benson 1983) shares similarities to the concentrative meditation technique and is adequate to control for the effects of relaxation that typically accompany meditation (Dunn et al. 1999).

Materials and methods

Subjects

Quantitative EEG data were recorded from 7 university students (3 men and 4 women; average age 25.42 years $\pm$ 1.75), classifying themselves as concentrative meditators. Seven control subjects (4 men, 3 women; average age 24.71 years $\pm$ 1.91) who reported no prior experience with meditation were utilized for comparison. The students were recruited from the Laurentian University community, as well as introduction to psychology courses. All subjects were right handed, and no participants had reported illnesses/diseases that would affect their EEG record. The meditating subjects had classified themselves as practicing a concentrative meditation technique and were asked to provide the experimenter with a brief write-up of the type

of mental engagement they used during meditation, so that this could be confirmed. According to previous research, concentrative meditators promote focus on a specific mental or sensory activity (Davidson and Goleman 1977), such as repeating a sound, an imagined image, focusing on the breath, or using a mantra (Barušs 2003; Brefczynski-Lewis et al. 2007; Cahn and Polich 2006). Participants in the current study all employed a concentrative technique with focus on the breath whereby they would focus on the physical sensations of the repetitive inhalation and exhalation as well as the sensation of air flowing in and out of the nostrils. Subjects self-reported the technique was practiced cumulatively for an average of 215.86 h ± 29 h with an average of 4.17 years of experience. All participants had reported that an ideal average length of time to practice their technique (i.e., average sitting length) was 14.43 min ± 1.17 min. Fifteen minutes was chosen for the allocated meditation time (or relaxation for controls), so that the length of recording time would be consistent for all participants.

Procedure

Participants individually attended one EEG session with the experimenter, which consisted of an eyes-closed non-meditating baseline EEG recording, 15 min of meditation with concurrent EEG measures and a post-meditation baseline recording. The control subjects practiced a modified version of Bensons' relaxation response (1983) in lieu of meditation, whereby they were asked to mentally repeat the word "one" to themselves over again and to gently bring back their focus to the mental repetition once they noticed their attention had drifted. All measurements were taken with the participants' eyes closed in an acoustic chamber. The Laurentian University Research Ethics Board approved the procedures for the current study.

Data acquisition

Quantitative EEG recordings were taken with a Mitsar 201 system amplifier which samples at 250 Hz. WinEEG version 2.82 software was utilized for data collection and the electrode cap (Electro-Cap International) utilized 19 AgCl electrodes, employing the International 10–20 standard method of electrode placement. Electrode sites included Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, and O2, where electrodes were linked to ears (A1 and A2) as reference for monopolar recordings. Impedance for all electrodes was maintained under 10 k Ohms. A 50- to 70-Hz notch filter was employed in WinEEG v2.82 software for all subjects to filter high-frequency noise during recording. The EEG record was visually inspected for artifacts, and the principal component analysis (PCA) method of artifact correction within winEEG v2.82 software was used where appropriate. Thirty-second artifact-free EEG epochs were utilized for the same time frame during the meditation/relaxation conditions. These epochs were divided into non-overlapping 2-s segments for analysis. The images generated by sLORETA were statistically tested for source localization differences during the different experimental conditions with nonparametric correction for multiple testing (Holmes et al. 1996), which is a feature selected for within sLORETA (Pascual-Marqui 2002).

Data processing and statistical analysis

Source localization analysis of the multi-channel EEG was completed with standardized low-resolution electromagnetic tomography (sLORETA; Pascual-Marqui et al. 2002). sLORETA uses standardized current density to calculate intracerebral generators and has low resolution, but zero localization error in the presence of measurement and biological noise (Pascual-Marqui et al. 2002). Cross-spectral analysis was completed on all (2 s) epochs, and paired *t*-tests without normalization were utilized within sLORETA to determine source localization throughout the telencephalon for each of the software's defined frequency bands, which include delta (1.5–4 Hz), theta (4–7.5 Hz) alpha-1 (7.5–10 Hz), alpha-2 (10–12.5 Hz), beta-1 (12.5–18 Hz), beta-2 (18–21 Hz), beta-3 (21–30 Hz), and gamma (30–45 Hz).

Results

When compared to their respective baselines, concentrative meditators and controls (practicing relaxation technique) demonstrate unique patterns of intracerebral activation, where concentrative meditation was primarily characterized by beta-1 source generation in the anterior cingulate (BA33) of the right limbic lobe ($t = -10.1$, $P < 0.001$) and beta-3 generation in the left precuneus (BA31, $t = -5.59$, $P < 0.001$) (See Fig. 1a and b). Furthermore, a decrease in gamma activity in the right inferior parietal lobule (BA40) was observed during meditation (Fig. 1c), when compared to baseline ($t = 8.65$, $P < 0.001$). For a summary of all results, see Table 1 for corresponding comparisons, cortical regions, and Montreal Neurological Institute (MNI) co-ordinates.

The pattern of activation characterizing a first-time practice of the relaxation response (modified technique) consisted of a decrease in beta-2 power in the right parahippocampal gyrus (BA28) of the limbic region ($t = 6.07$, $P < 0.0005$) and a decrease in the right inferior parietal lobule (BA40) in delta activity during relaxation ($t = 5.28$,

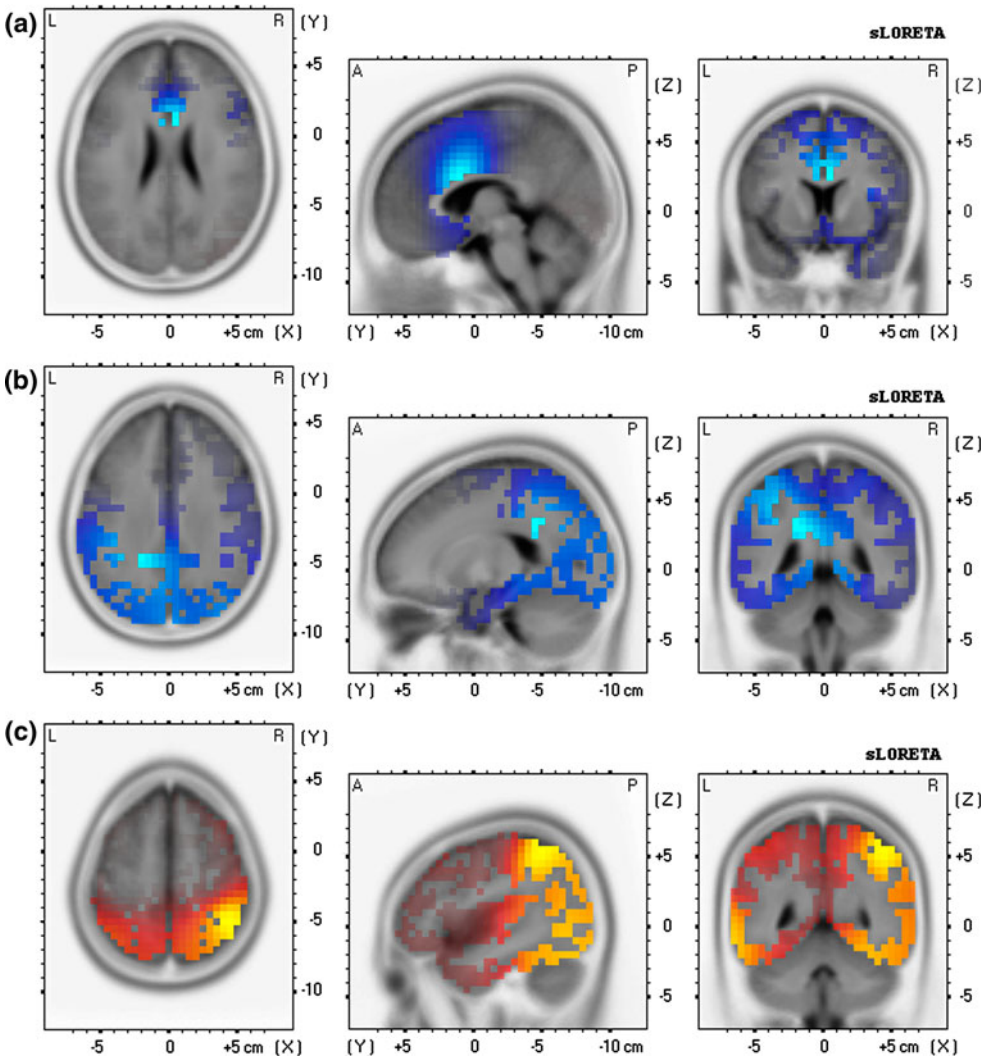

Fig. 1 Increased beta-1 activity in the **a** anterior cingulate (*blue*) and beta-3 activity **b** in the precuneus (*blue*) during meditation, accompanied by a decrease (*yellow*) in the **c** right inferior parietal lobule during meditation, when compared to baseline

Table 1 Summary of significant findings, outlining condition, spectral band, cortical regions, and Montreal Neurological Institute (MNI) co-ordinates

Condition	Frequency	Region	X	Y	Z
Concentrative meditation > baseline	Beta-1	BA33	5	10	25
Concentrative meditation > baseline	Beta-3	BA31	−20	−45	35
Concentrative meditation < baseline	Gamma	BA40	45	−50	55
Relaxation < baseline	Beta-2	BA28	15	−10	−15
Relaxation < baseline	Delta	BA40	45	−40	50
Relaxation > concentrative meditation	Beta-1	BA10	30	60	15
Relaxation > concentrative meditation	Gamma	BA11	30	60	−10
Relaxation > concentrative meditation	Gamma	BA45	55	30	20
Relaxation < concentrative meditation*	Beta-2	BA34	20	0	−15
Relaxation < concentrative meditation*	Beta-2	BA20	55	−20	−30
Relaxation < concentrative meditation*	Beta-1	BA20	65	−25	−20
Relaxation < concentrative meditation*	Beta-3	BA21	65	−25	−20

* Controlled for baseline

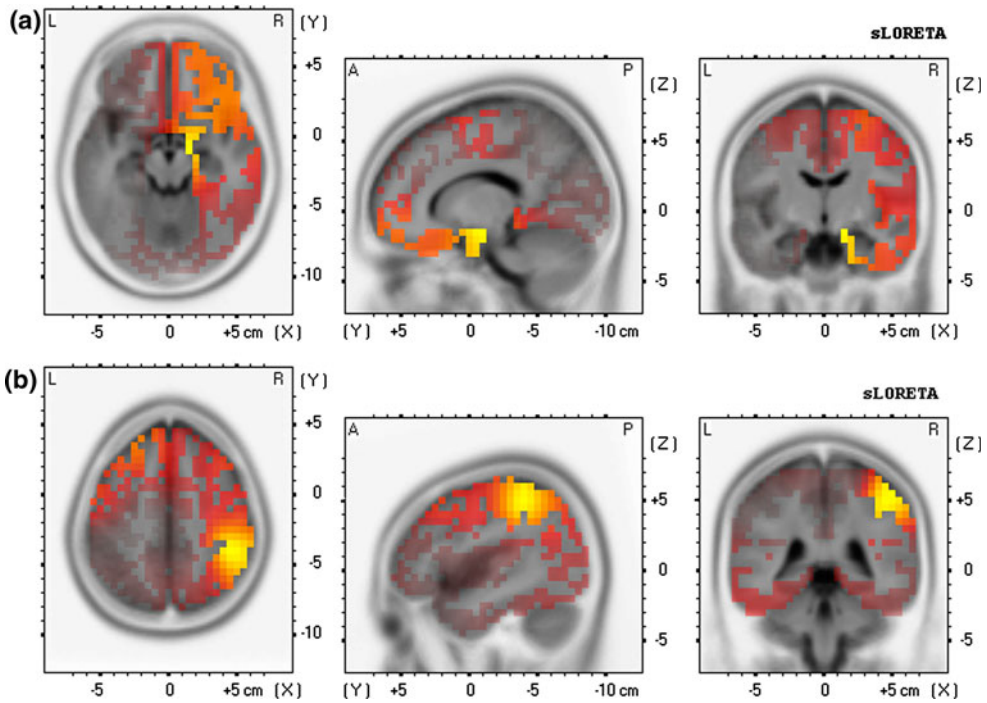

Fig. 2 Decreased activity in the **a** right parahippocampal gyrus and **b** right inferior parietal lobule during relaxation, when compared to baseline

$P < 0.0005$), when compared to baseline (Fig. 2a and b). Although the effects were observed in different spectral frequencies, both the relaxation and the meditation practices were characterized by a decrease in right inferior parietal lobule (BA40) activity, when compared to baseline.

Once the intracerebral source generators characterizing the meditation and relaxation practices were discerned (above), a comparison between groups was conducted. The results from this analysis indicated that control subjects displayed significantly greater lower spectrum beta and gamma power in the right frontal regions, including the middle (BA10, $t = 8.49$) superior (BA11, $t = 6.25$) and inferior (BA45, $t = 7.32$) gyri ($P < 0.0005$ for all), when compared to meditators (Fig. 3a, b, c).

To further discern the electrical variations within the cerebrum characterizing these two groups, an sLORETA analysis was completed which controlled for baseline differences, as previous research has demonstrated that meditators may differ from controls in resting baseline states (Cahn and Polich 2006; Tei et al. 2009). Controlling for an eyes-closed baseline revealed increased activity throughout the right temporal and limbic region during meditation, when compared to relaxation. Beta-2 activity in the right parahippocampal (BA34, $t = 4.08$, $P < 0.0005$) gyrus of the limbic lobe and fusiform gyrus (BA20, $t = 4.35$, $P < 0.001$), beta-1 activity in the right inferior temporal (BA20, $t = 4.12$, $P < 0.001$) gyrus, and beta-3 in the right middle temporal gyrus (BA21, $t = 4.69$, $P < 0.001$) were all greater during meditation (Fig. 4a, b, c).

Discussion

The findings from this study are novel in that this meditation technique has not been investigated with EEG source localization. With respect to other putative experimental results, the findings from the current study are most comparable to the Travis et al. (2009) study. Compared to previous research by Travis et al. whereby the authors implemented a TM, intervention-training program revealed a pattern of activation where similar regions were also activated during meditation and baseline; however, some differences emerge. Similarly, both TM (Travis et al. 2009) and concentrative meditation display significant increases in the anterior cingulate (Fig. 1a) and precuneus (Fig. 1b) during meditation. In contrast, TM was also characterized by an increase in left lingual gyrus and parahippocampus activity, whereas the current study did not observe this activity for the concentrative meditators. This would be consistent with previous research that TM and concentrative meditation, although both employing concentration practices, are unique forms of meditation (Tart 1983; Barušs 2003) and may be considered different altered states of consciousness (Cahn and Polich 2006).

The unique pattern of intracerebral source generation outlined in this study, when compared to the Travis et al. (2009) study, may be a reflection of the type of mental engagement involved in both TM and concentrative meditation. Although TM has often been included in the focused attention meditation category (Barušs 2003), TM practice emphasized ease or absence of effort in

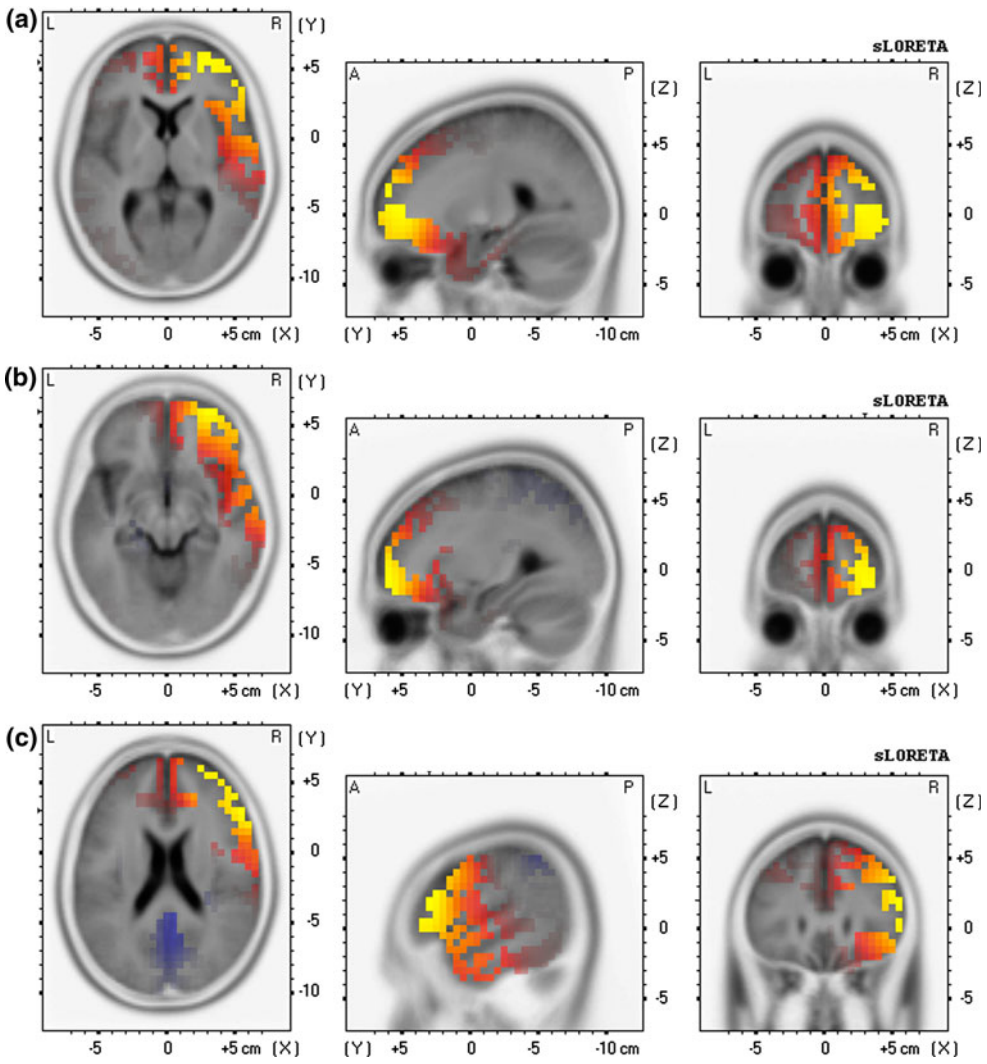

Fig. 3 Increased activity in the right middle (**a**) superior (**b**), and inferior (**c**) frontal gyri in controls during relaxation, when compared to meditators during meditation

maintaining concentration (Raffone and Srinivasan 2010). Furthermore, when transcendental awareness is achieved, it is hypothesized to be characterized by the absence of concentration, loss of time, space, and bodily sense (Raffone and Srinivasan 2010; Arenander and Travis 2004; Travis and Pearson 2000). Although activation of some of the same brain regions occur (when compared to the Travis et al. 2009 study), it is prudent to note that the frequencies within which these results were found was not the same; hence, the corresponding cognitive processes are very different, which would be reflective of the type of mental engagement involved in both TM and concentrative meditation (Travis and Shear in press).

TM involves practices that borrow techniques from both the focused attention and open monitoring meditation practices which could explain the variations in spectral frequencies observed in the current study, when compared to the Travis et al. (2009) study, whereby alpha generations may be more typical of the TM technique as it is often described as occurring without effort (Travis and Shear in press) and beta spectrum generations are hypothesized to be more typical of a concentrative technique (i.e., Dunn et al. 1999; Travis and Shear in press), since beta activity is associated with greater levels of arousal and cognitive processing than alpha (Zillmer and Spiers 2001). The ease or absence of concentration during TM is not typically characteristic of a purely concentrative meditation technique and these differences in mental engagement characterizing each meditation practice may be reflected in the unique pattern of intracerebral source generation as well as the respective spectral frequencies, as observed in the current study.

The concentration meditation condition was characterized not only by beta-1 generation in the anterior cingulate (Fig. 1a), but also by beta-3 generation in the precuneus (Fig. 1b). Broadmann's Area 33 of the anterior cingulate is part of the affective division and has been implicated in regulating autonomic functions, being involved in

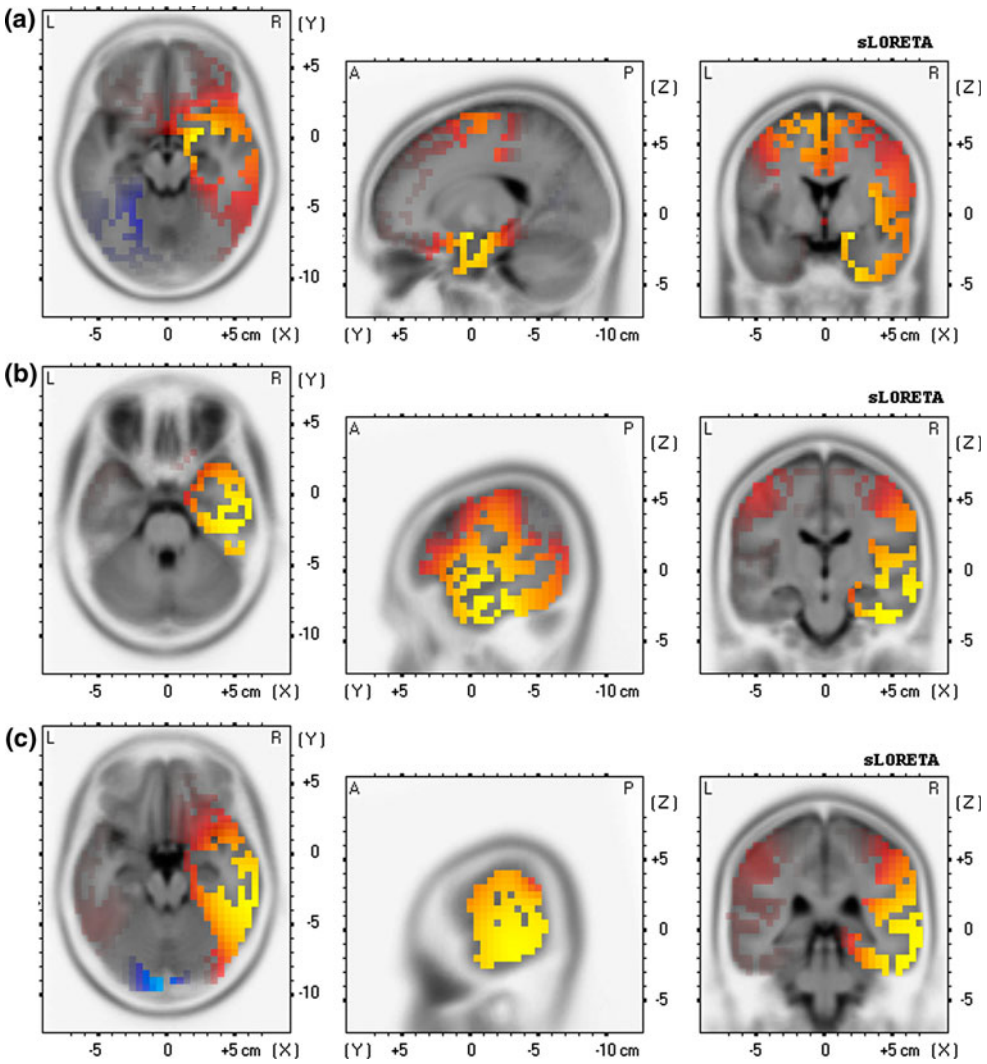

Fig. 4 After controlling for baseline, meditators demonstrate greater activity in the right parahippocampal (**a**) inferior temporal (**b**), and fusiform gyri (**c**) during meditation, when compared to controls during relaxation

conditioned emotional learning, expressing internal states, and assigning emotional valence to internal and external stimuli (Devinsky et al. 1995). Its activity has also been correlated with attention demanding tasks (Gevins et al. 1997) and is a marker of increased attentional focus in meditative states (Cahn and Polich 2006). The precuneus has been implicated in restoration of conscious awareness states (Laureys et al. 1999), as well as self-centered imagery and episodic memory retrieval (Cavanna and Trimble 2006). Furthermore, these areas are hypothesized to be part of the DMN and Travis et al. (2009) suggest that meditation induced increases in the DMN may lead to a foundational state of cerebral functioning that may underlie eyes-closed rest and focused cognitive processing.

Subjective reports on the effects of meditation, aside from stress reduction benefits and positive affect (Grossman et al. 2004), have included changes in perceptual awareness (Barušs 2003; Carter et al. 2005; Nicholson 2010). After regular meditation practice, subjects often report changes in the awareness of their surrounding external and internal environments (Brown 1977). It was previously hypothesized that these subjective changes in awareness and consequent perception were due to a change in the subjective temporal experience of "now" (Brown et al. 1984). Based on a neuroimaging study during a time dilation illusion by Wittman et al., this hypothesis seems plausible due to the activation of specific structures during the presence of time dilation. Time dilation has been observed when targets are perceived as looming toward a subject, and functional magnetic resonance imaging (fMRI) reveals that this time dilation occurs in conjunction with the activation of several midline structures, such as the anterior cingulate and left precuneus (Whittman et al. 2010).

The midline structures (i.e., anterior cingulate and precuneus), which appear to have differential activation during meditation (see Fig. 1a and b), have been implicated in the default mode network (DMN) (Raichle et al. 2001), as well as in the temporal dilation illusion (Whittman et al. 2010).

These structures display greater activation during self-referential mental activity and during tasks involving self-projection. Whittman et al. (2010) have demonstrated that the illusion of temporal dilation is due to activation of these midline areas, which have been implicated in cognitive control and subjective awareness. They have interpreted that the involvement of midline structures in time dilation as evidence that time perception is related to self-referential processing. Interpretation of the results from the current study would indicate that there might be a possible connection between the activation of the DMN structures associated with meditation and this may allude to previously reported changes in the meditators' subjective awareness (Barušs 2003; Nicholson 2010) based on the results by Whittman et al. (2010).

The modified relaxation response in meditation-naïve participants was characterized by lower activity in the parahippocampal gyrus and inferior parietal lobule. Studies in primates and lower mammalian species suggest that the parahippocampal regions contribute substantially to memory processes and provide the major polysensory input to the hippocampus (Burwell 2000). Since increased activation or gray matter volumes in the right parahippocampus have been implicated in panic (Massana et al. 2003; George and Ballenger 1992) and anxiety symptoms (Osuch Ketter et al. 2000), this decrease during the relaxation response (modified) may indicate that subjects are less anxious than during baseline. This may be inadvertent evidence that participants were actually relaxing, which would provide external validity for the relaxation response as quantitative electroencephalographic support is lacking for this technique. This is an interesting finding because parahippocampal regions typically become *more* activated during meditation (Lazar et al. 2000); however, this provides evidence to support the hypothesis that the relaxation response represents a unique form of consciousness separate from meditation (Dunn et al. 1999).

Although the effects were observed in different spectral frequencies, both the relaxation and meditation practices were characterized by a decrease in right inferior parietal lobule (BA40) activity, when compared to baseline. Enhanced activity in the right inferior parietal lobule has been associated with sympathetic arousal (Critchley et al. 2000) and has been strongly implicated in directing attention to external stimuli (Fink et al. 1996). These results would suggest that during both relaxation and meditation, subjects are recruiting less attentional mechanisms to focus on their external environment, which may also be associated with a concomitant decrease in temporal and spatial processing (Batelli et al. 2008), as inferred by other EEG studies which focus on concentrative meditation (Baijal and Srinivasan 2010). As the differences were observed in delta and gamma frequencies for controls and meditators, respectively, the associated functional or behavioral correlates of these EEG frequencies may suggest that meditators are more highly engaged (gamma) in directing attention to external stimuli than are the controls (delta) during baseline recordings. Since activity in the concentrative meditators (during meditation) increased in regions specifically identified in a self-referential default mode network, the results imply less external awareness and increased internal (i.e., self-referential) awareness during meditation. For the participants practicing the relaxation response, there is no concomitant increase in regions associated with the self or internal states. One must consider that these recordings were taken during the participants' first experiences with practicing the relaxation response and this trade-off between external vs internal focus may only appear after sufficient experience with detracting from focus on external stimuli.

In meditators, when compared to controls, one might expect a reduced activation in neural systems implicated in regulating attention, such as the right frontal region (Deutsch et al. 1987; Rueckert and Grafman 1996; Aron et al. 2003; Wilkins et al. 1987); this decrease might be associated with optimized performance in sustained and selective attention tasks (Brefczynski-Lewis et al. 2007). Since the meditators have continued experience ($\sim$200 h) with this practice, less attentional mechanisms are required to sustain the focused attention, whereas meditation-naïve participants would have to recruit more attentional resources to sustain focused attention, which is commensurate with the neural efficiency hypothesis of skill learning (Grabner et al. 2006) and may be represented in the greater right frontal activity demonstrated by controls. However, these results may be due to baseline differences that are present between meditators and controls, as sLORETA analysis, which controlled for baseline differences, did not yield the same pattern of intracerebral activation. It would be reasonable to hypothesize that these results may be related to structural differences in the frontal lobe as Lazar et al. (2000) have demonstrated through MRI that the right middle and superior frontal sulci were significantly thicker in meditators than in controls.

Previously, it was hypothesized that general or Transcendental Meditation (TM) may be considered a form of "cognitive kindling", as meditators reported a wider range of complex partial epileptic signs, such as widened affect and creativity, than controls (Persinger 1993). The focus of such activity would be primarily localized to the right temporal region (Persinger 1984; Makarec and Persinger 1990). The results from this study would support the hypothesis that general meditation (i.e., concentrative meditation) may represent a type of cognitive kindling where significant increases throughout the right temporal and limbic region occur in meditators, when compared to

controls. TM is often considered a variant form of the concentrative technique (Davidson and Goleman 1977) as they both employ mental repetition and attentional focus, so although direct comparisons cannot be made between the two, inferences can be made. The basis for the cognitive kindling hypothesis, as well as the complex partial signs reported by meditators, center on the activity of the right temporal region. If one is engaging the right temporal regions via self-stimulation, during contemplative-like practices for approximately 15 min/day for a protracted period of time, this may constitute cognitive kindling which would occur as a function of appropriate mental repetition (i.e., focus on breath, mantra, etc.). Whether or not recruitment of these neuronal pathways serves an adaptive function, such as enhanced creativity (Persinger 1993), remains to be determined.

Conclusion

The results from this study suggest that the pattern of activation that accompanies the concentrative meditation technique may be associated with decreased external awareness and increased self-referential processing, whereas meditation-naïve participants only demonstrate decreased activity in regions responsible for processing information from the external environment. These results may have implications for the role of the self in meditational states. Furthermore, our results reveal that meditation-naïve participants may have to employ more attentional mechanisms (right frontal) during the relaxation technique than concentrative meditators during meditation because they do not have continued experience with such practices. The pattern of activation observed throughout the right temporal and limbic region during meditation may provide support for the cognitive kindling hypothesis and may lend insight into a possible mechanism by which creative states are enhanced in meditators.

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